Master’s Thesis: Towards Novel Electrical Insulation Systems for Nb3Sn High Field Magnets (EDMS 3168202)

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Introduction

Two parallel projects, disconnected (but actually connected), contributed to my **Master's thesis** at CERN:

1) **Studies on fiber fraction in composite electrical insulations**
   - Study the effects of fiber content on electrical properties of epoxy impregnated fiberglass.

2) **Electrical (HV) 10-Stacks**
   - Validate electrical insulation systems in a layout resembling actual magnets.

Content

- **Fiber Volume Fraction Study on Laminates**
  - Produced Samples
  - Dielectric Spectroscopy
  - Resistivity
  - Dielectric Strength
  - Discussion

- **HV 10-Stack**
  - Produced Stacks
  - Insulation Resistance Tests
  - Partial Discharges Analysis
  - Discussion

- **Conclusion and Future Work**

Fiber Volume Fraction Study on Laminates

Produced Samples

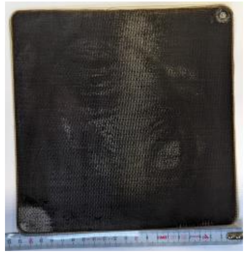
[A] High Vf 636

[B] Med Vf 493

[C] Low Vf 493

[D] Very Low Vf 493

[E] Low Vf HT 493



[F] Med Vf HT 493

[G] High Vf HT 636

- Study the effects of fiber content and of Heat-Treatment (48h plateau at 650°C in Argon)
- Plates with High, Medium, Low Vf, are all made with same fiber layout respectively
- S2 Glass fiber impregnated with CTD101K epoxy (baseline)

Plate	[A]	[B]	[C]	[D]	[E]	[F]	[G]
Number of Mats	15	7	2	1	2	7	15
Tex	11	33	66	66	66	33	11
Sizing	636	492	493	493	493	493	636
Heat Treatment	No	No	No	No	Yes	Yes	Yes
Nominal Mat Thickness (mm)	0.05	0.09	0.25	0.25	0.25	0.09	0.05
Plate thickness (mm)	0.755	0.691	0.598	0.366	0.575	0.639	0.773
Plate weight (g)	49.23	51.76	43.34	92.30	42.10	49.10	48.70
Plate Area (mm^2)	35914.00	44014.00	44014.00	159914.00	44014.00	44014.00	35914.00
Plate density (g/mm^3)	1.82E-03	1.70E-03	1.65E-03	1.58E-03	1.66E-03	1.75E-03	1.75E-03
Fabric weight (g/mm^2)	6.18E-05	1.03E-04	2.69E-04	2.69E-04	2.69E-04	1.03E-04	6.18E-05
Volume fraction (layers method)	0.50	0.42	0.37	0.30	0.38	0.46	0.49
Volume fraction (density method)	0.48	0.39	0.34	0.29	0.36	0.42	0.43
EDMS	3010815	3026056	3010825	3026060	3026058	3033576	3078008

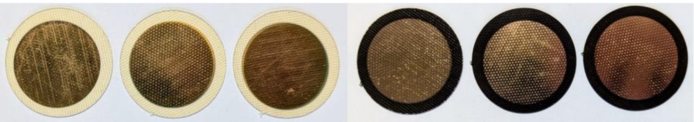
$$V_f = \frac{\rho_c - \rho_r}{\rho_f - \rho_r}$$

ρ_c −Density of the composite (g/m3)
ρ_r −Density of the resin (g/m3)
ρ_f −Density of the fiber (g/m3)

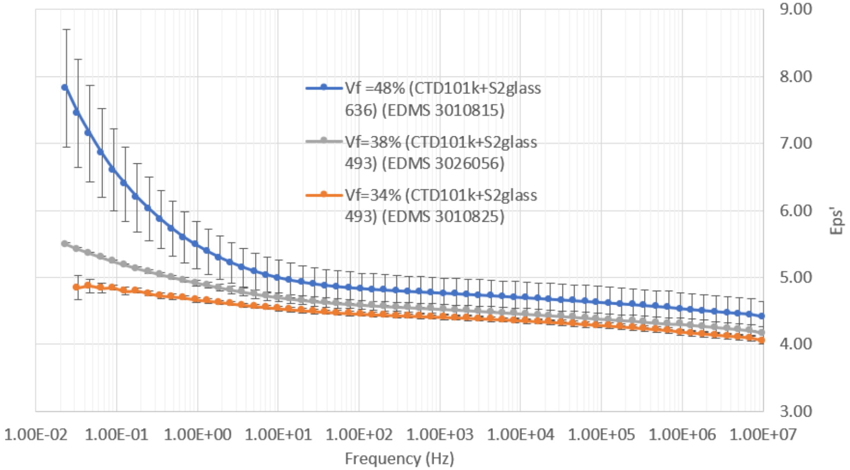
$$V_f = \frac{n \cdot \rho_m}{t \cdot \rho_f}$$

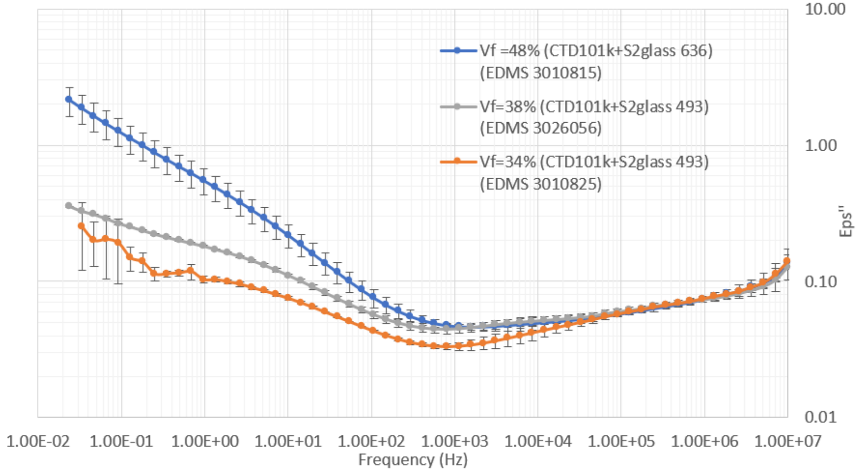
n −Number of mats in the composite
ρ_m −Areal density of the fabric (g/m2)
ρ_f −Density of the fiber (g/m3)

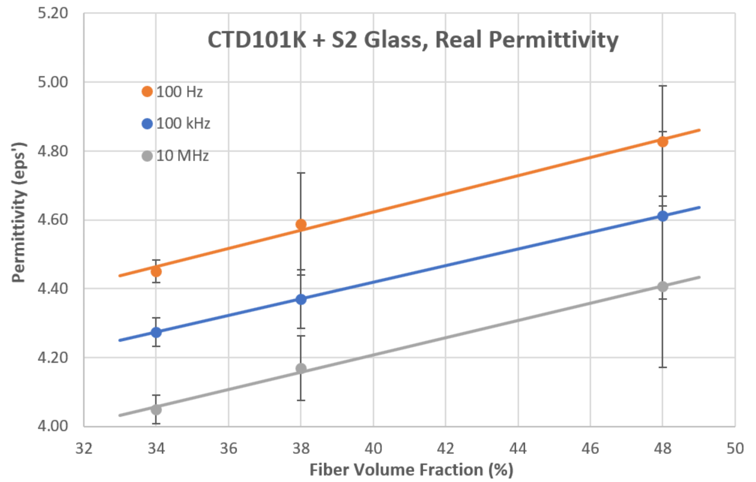
Dielectric Spectroscopy



As-Received Fiber + CTD101k Samples:





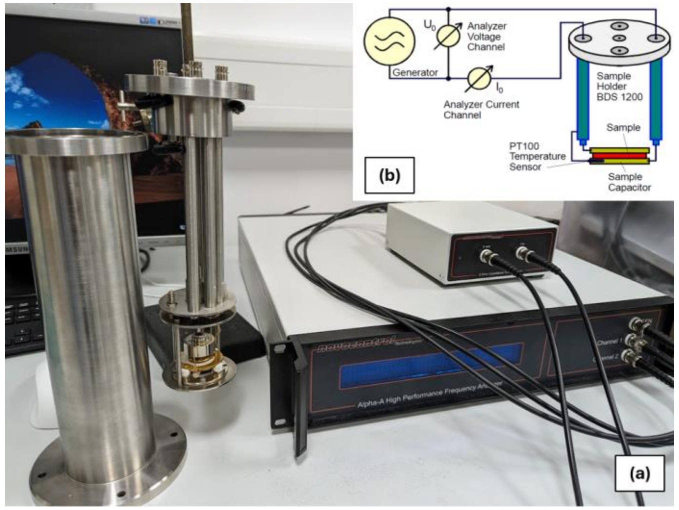


ASTM D150 Standard

Typical Permittivity values of pure materials:

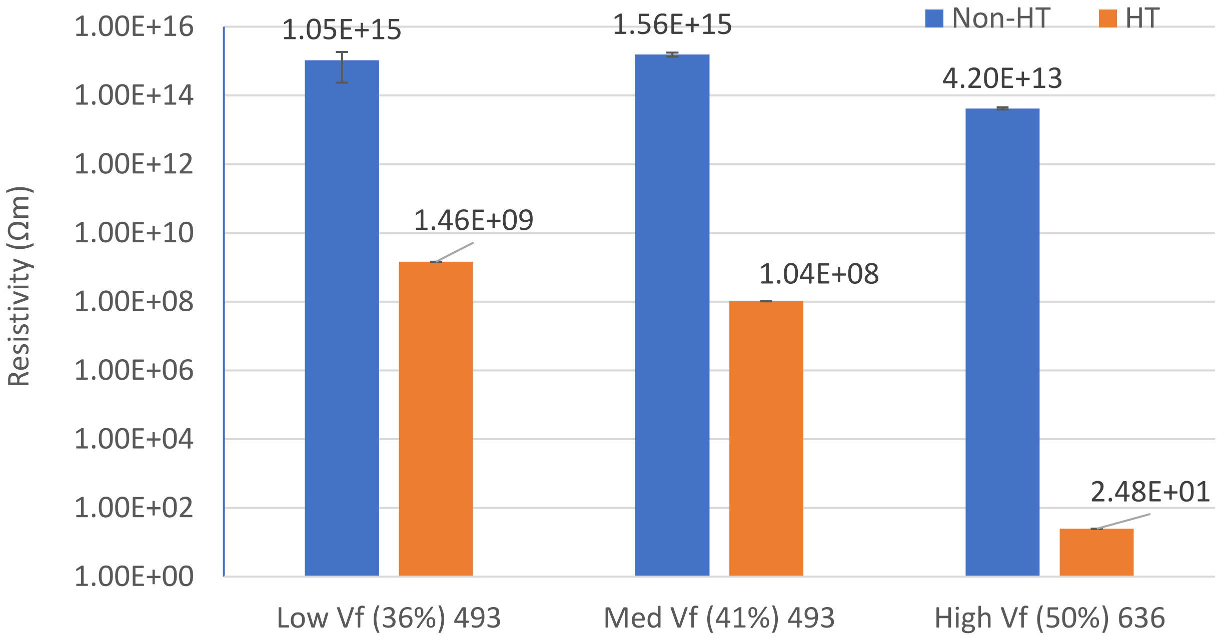
$$\varepsilon_{S2Glass} = 5.2$$
$$\varepsilon_{Epoxy} = 3 - 4.6$$

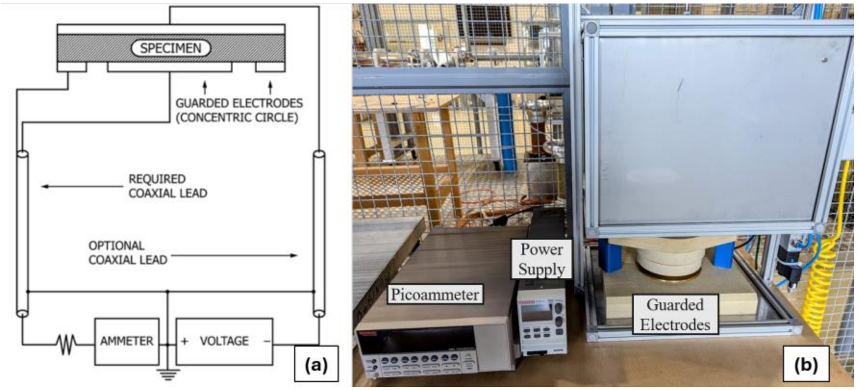
- **Linear increment of epsilon with fiber content**
- At low frequencies, a convolution of peaks due to interfaces in eps''



Resistivity

ASTM D257-07 Standard





Typical Resistivity values of pure materials:

$$\rho_{Glass} = 10^{8}\ \Omega m$$

$$\rho_{Epoxy} = 10^{11} - 10^{13}\ \Omega m$$

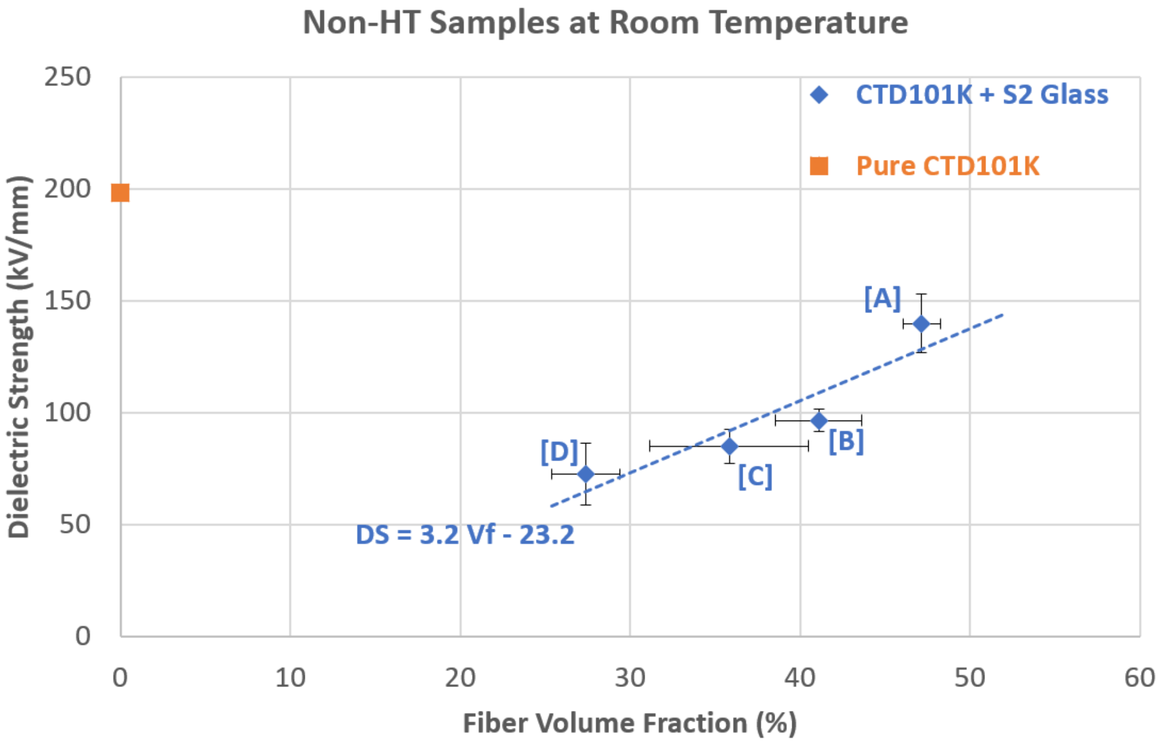
HT

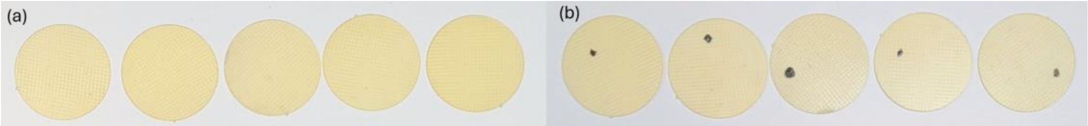
- At least **6 orders of magnitude of resistivity lost**
- Higher fiber fraction → Greater resistivity degradation
- **Percolation threshold** reached for 636 sizing plate

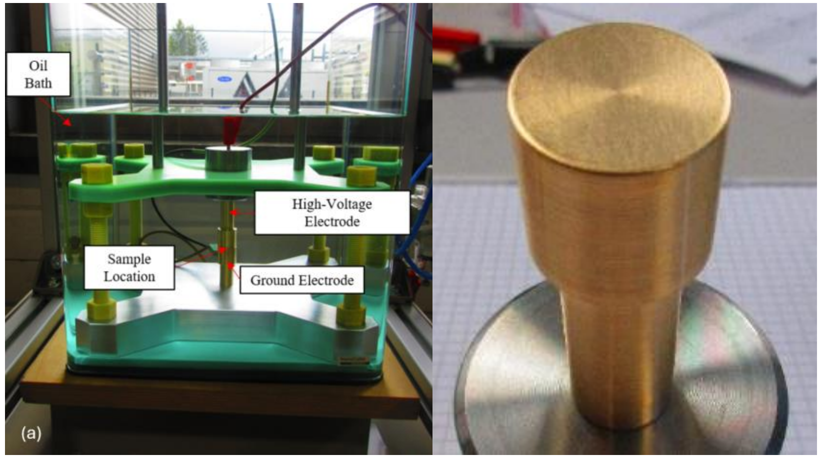
Non-HT

- **Higher glass content composites were expected to have lower Resistivity**
- Vf = 36% and Vf = 41% measurements near to the full scale of the instrument
- More tests are needed

Dielectric Strength (1/2)





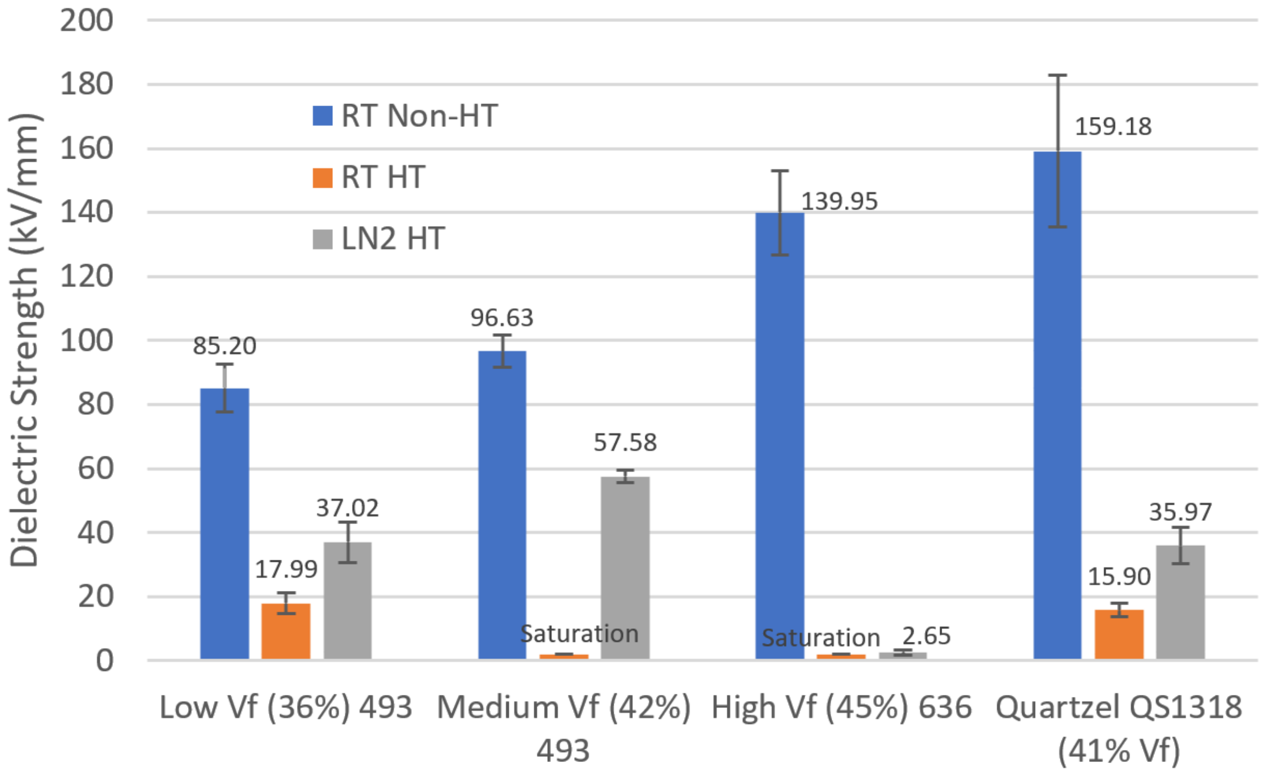


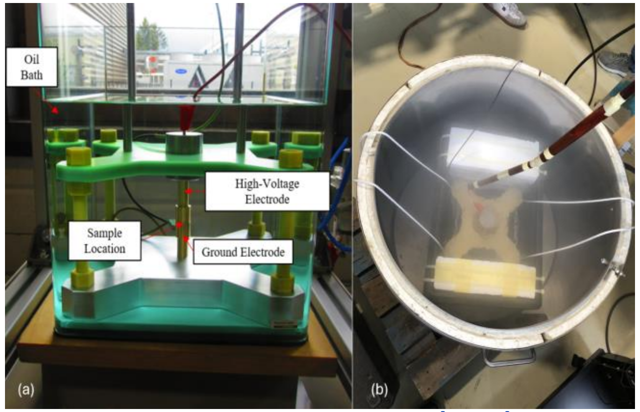
ASTM D3755-20 Standard

- Decline in dielectric strength from pure CTD101K to the composite material at low fiber fractions (field amplification on interfaces).
- Later, **rule of mixture is applicable**: glass has higher dielectric strength than epoxy (+higher treeing resistance).

Dielectric Strength (2/2)

- Decline in dielectric strength from as-received (Non-HT) to heat-treated (HT) fibers.





ASTM D3755-20 Standard

At cryogenic temperatures (LN2) conductive component of the current is suppressed.

- Higher fiber content (not too high!) showed improved dielectric strength as at room temperature
- High Vf (45%) and 636 sizing still above percolation threshold

Discussion

High fiber content insulation showed:

- **Higher dielectric strength**
- **Possibly lower resistivity** (more tested are needed)
- **Higher permittivity**

- Higher properties **degradation** following **heat treatment** for **higher fiber content** laminates

- The **advantages of more fiber are overshadowed by the carbonized sizing**

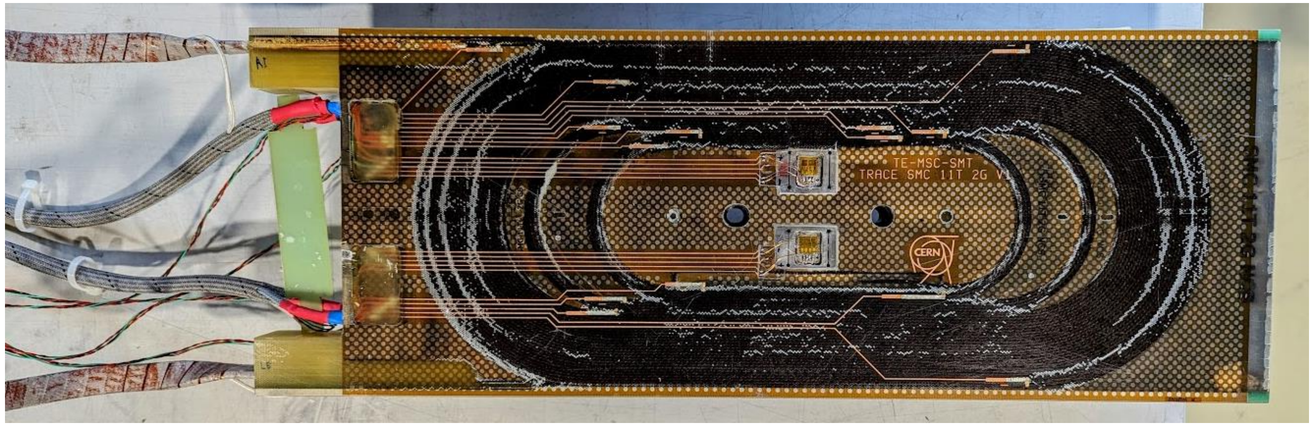
HV 10-Stacks

Cable Stacks

- Intermediate step between **plates** and **short model coils (SMC)**

Epoxy impregnated S2-Glass fiber plate

Cable 10-Stack

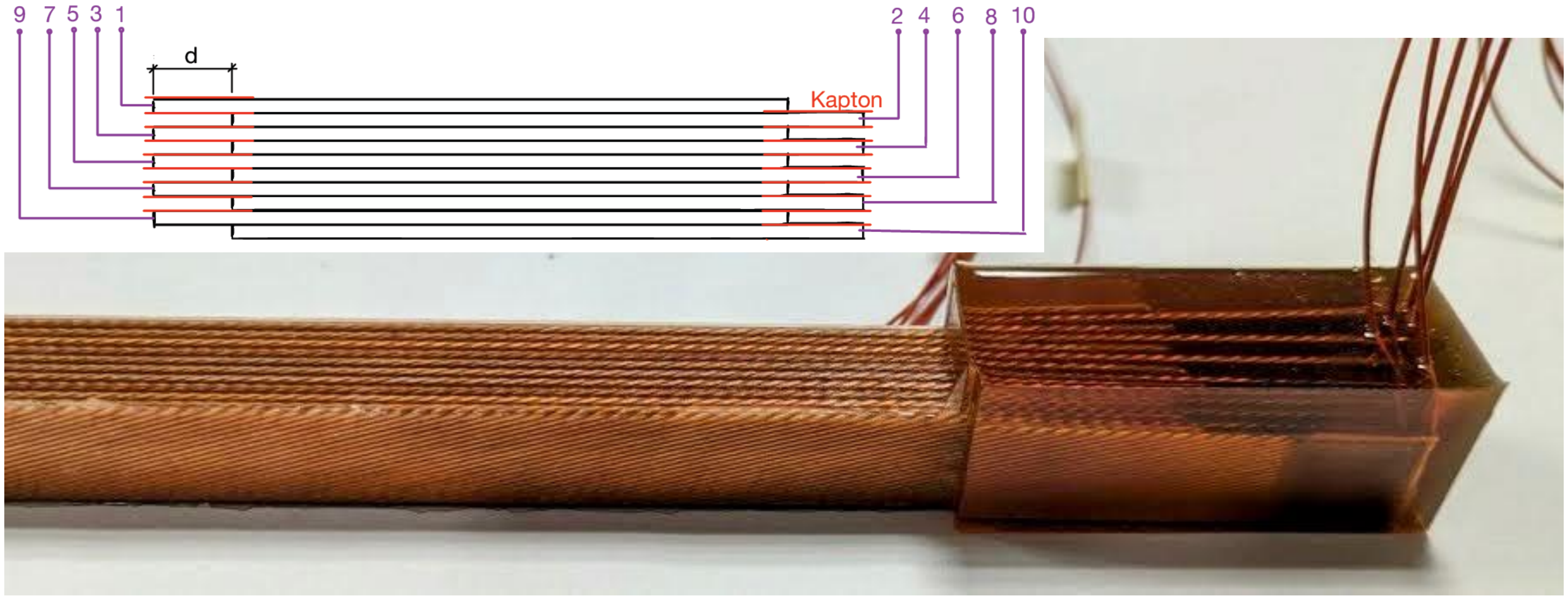


SMC 11T 103b

- **Validation of materials selected (in the real configuration) and in combination with cables** (adhesion effects, charge injection, thermal contraction…)

Electrical 10-Stack: HV (High Voltage) 10-Stack

10 Rutherford cables (MQXF type) instrumented for electrical testing, piled and epoxy impregnated

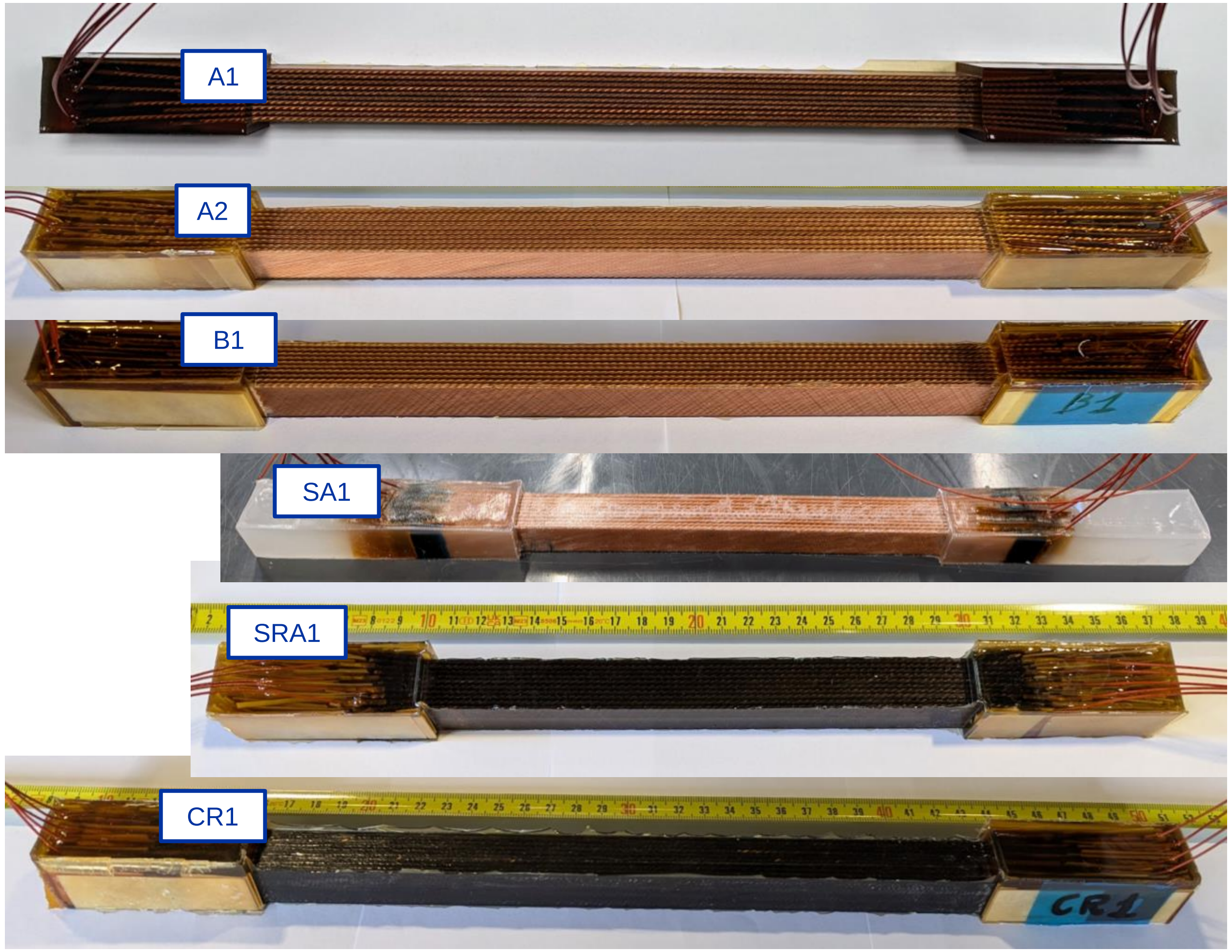


First impregnated HV 10-Stack

Open Impregnation Mould for HV 10-Stack

- Materials validation (Epoxy, fiber)
- Fiber layout validation

Produced Stacks



: Baseline Non-Reacted (CTD101K + S2 Glass 933)

: Polab Mix + S2 Glass 933 (Baseline)

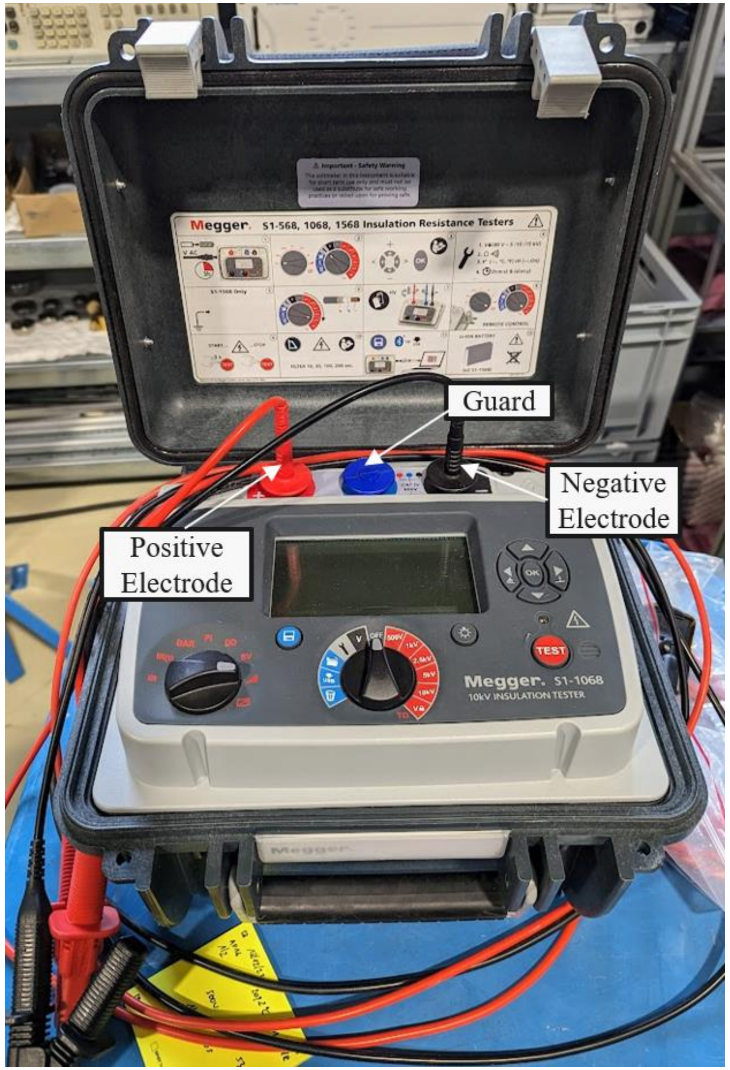
: CTD101K + S2 Glass 11 tex 636, 2 layers

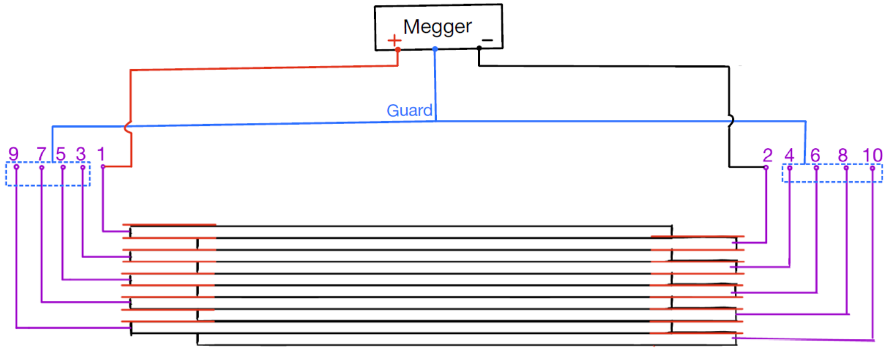
: Polarit A55 (Wax) + S2 Glass 933 (Baseline)

: Baseline Reacted (CTD101K + S2 Glass 933)

: CTD101K + Quartzel 17 tex QS1318, 2 layers

Insulation Resistance (IR)



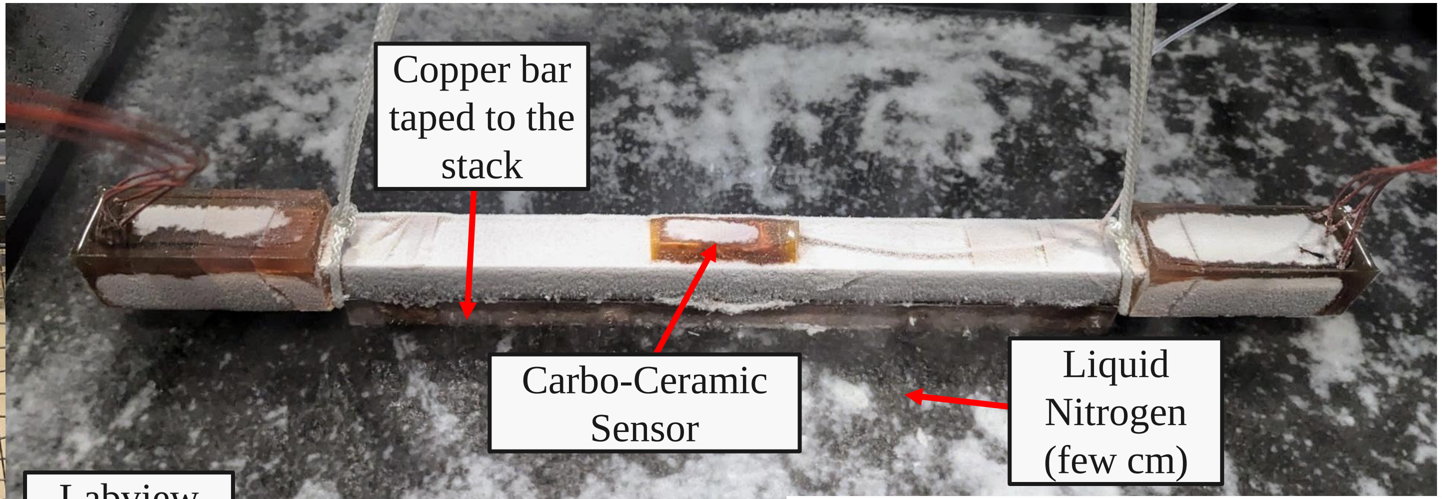


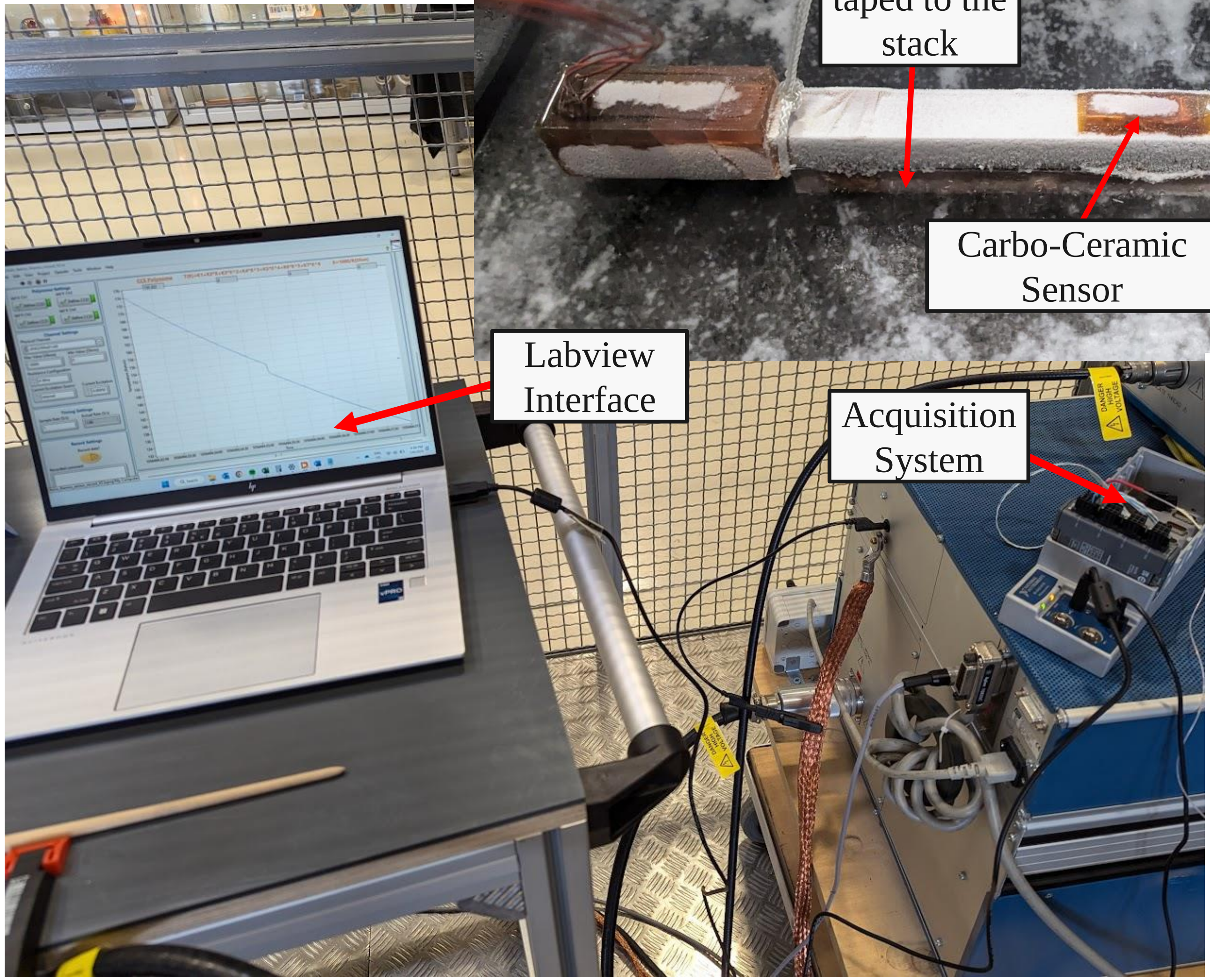
- Electrical insulation tester: applies voltages DC in the range [500 V - 10 kV] and measures current to obtain resistance
- **Guard** is a low-impedance path used to avoid leakage currents

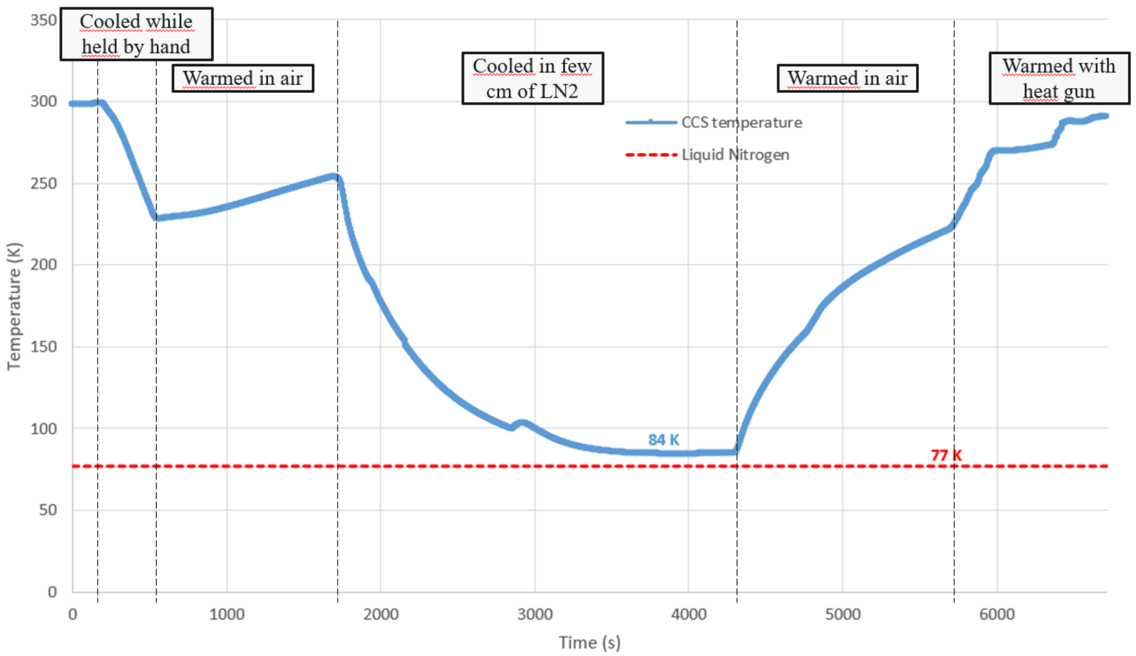
- Insulation tested at **2.5 kV**, **resistance recorded at 30 s and 300 s**
  - Resistance tends to grow with time due to the extinction of polarization currents
- Low IR or low **Polarization Index (PI)** could be diagnostic of insulation defects

$$\mathrm{PI} = \frac{R_{300}}{R_{30}}$$

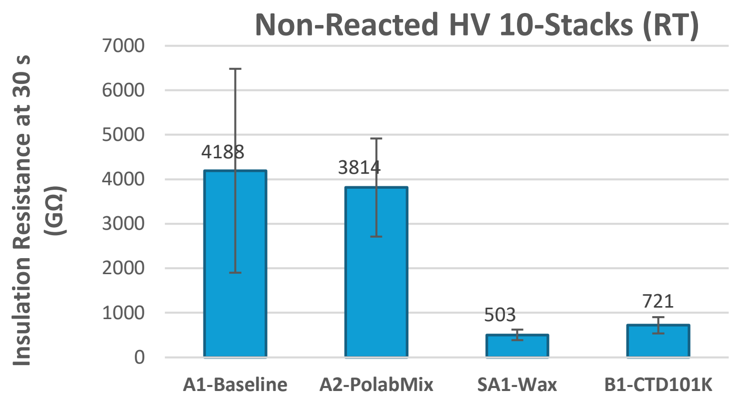
Stack Thermalization in LN2





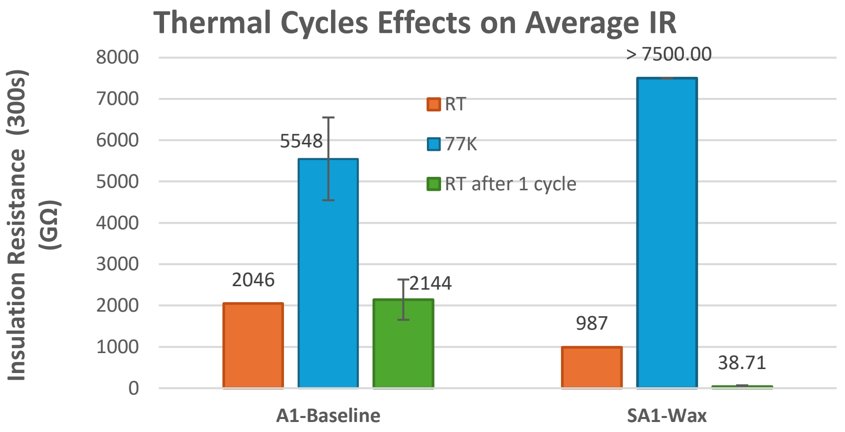


Insulation Resistance Testing

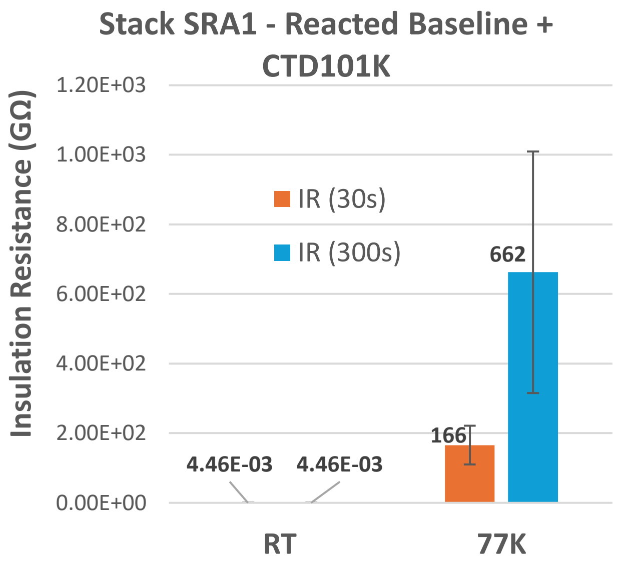


Stack B1 double layer 636 sizing: Lower IR

- More parallel paths of fiber
- 636 sizing without coupling agent

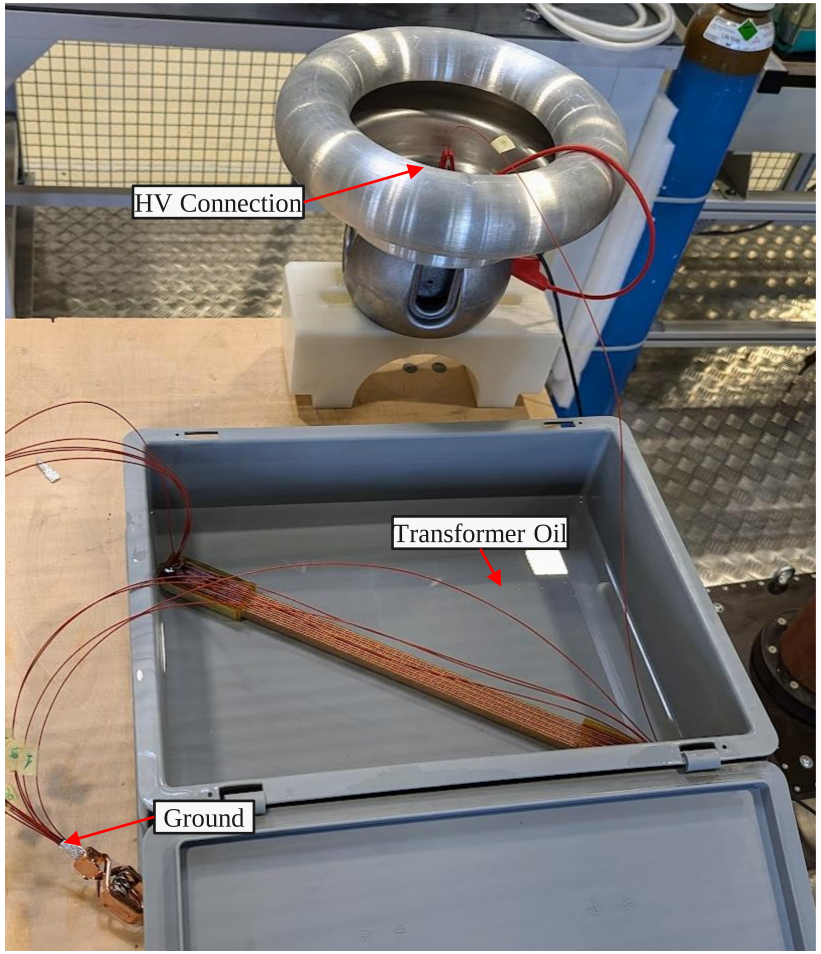


CTD101K resists extremely well to thermal cycles, Wax needs improvements

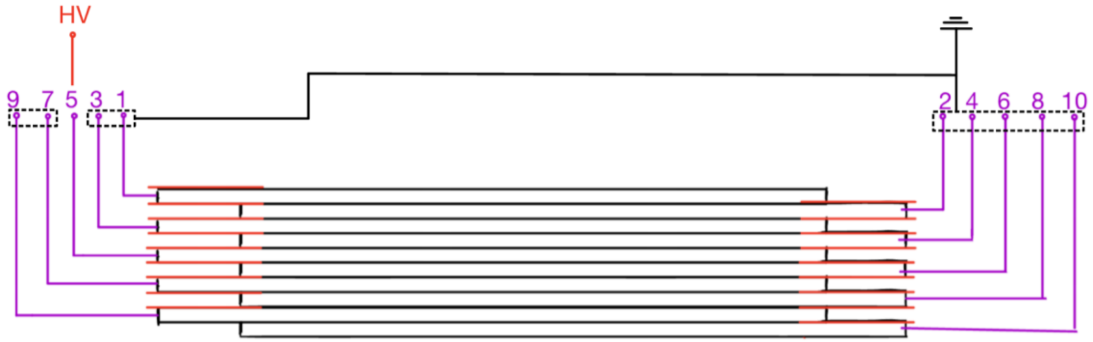


- Great improvement of IR at 77 K (6 orders of magnitude)
- CR1 (Double layer reacted Quartzel) remains in the order of few MΩ

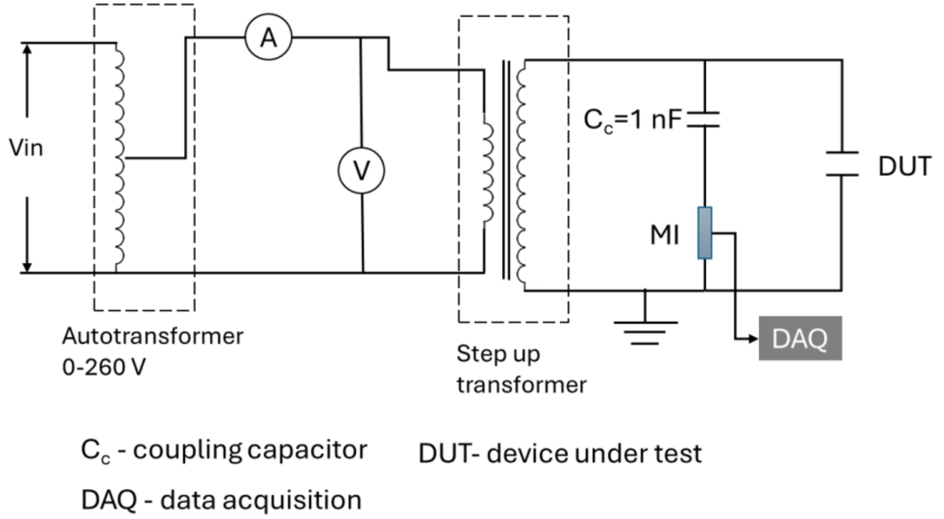
Partial Discharge Analysis



Oil avoids surface discharges



Turn x to HV, other turns to Ground



Electrical Scheme of the PD setup

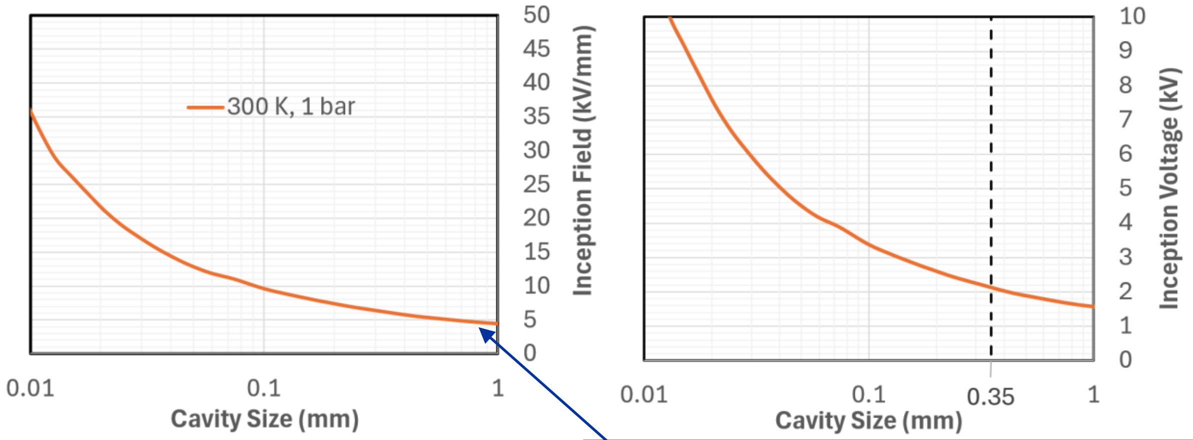
Partial Discharge Analysis

PD Typologies:

- Surface
- Internal (voids in epoxy)
- Internal with surface behavior (along cracks or delaminations)

Identified by:

- Inception voltage (V).
- Amplitude of the discharge (pC).
- PD pattern and TF map clusters.
- Evolution of the PD signal as the applied voltage increases.



From Paschen curves available on EDMS also for other gases and pressure/temperatures

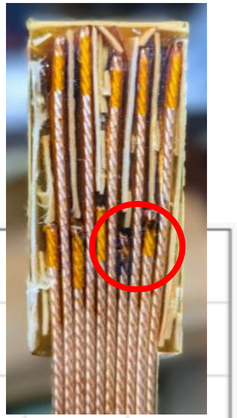
Internal defect size estimation:

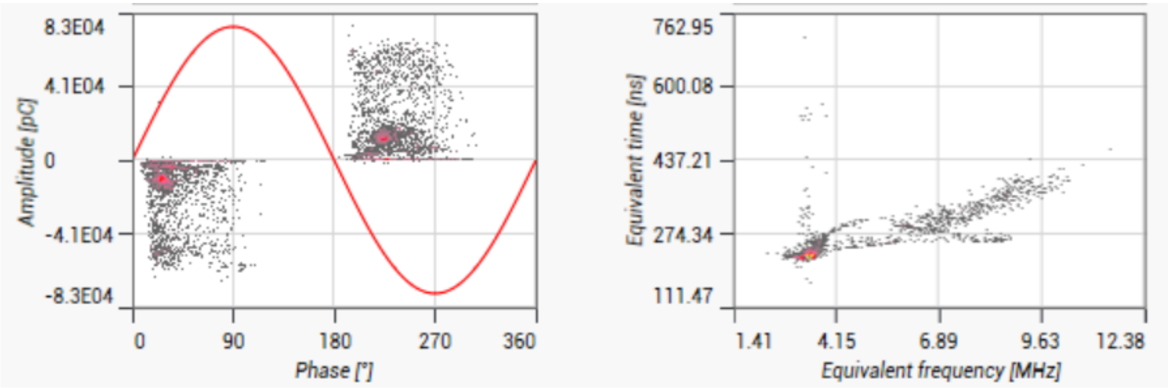
$$E_{\text{cavity}} = f \cdot E_0$$

E_0: Field in the dielectric material
$f \cong 1.3$ (spherical cavities)
$f \cong \varepsilon_r$ (flat cavities, oblate)

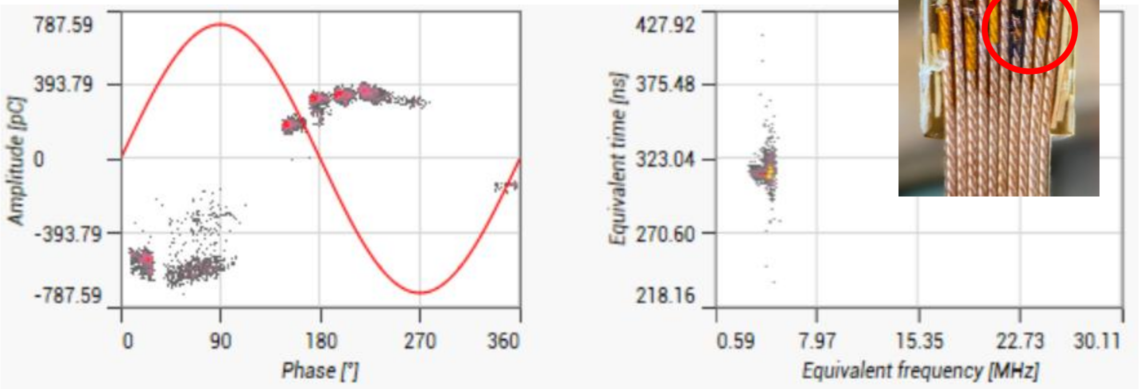
At room temperature, just Non-Reacted stacks could have been tested (A2, B1, A1)

PD Typologies (Examples)

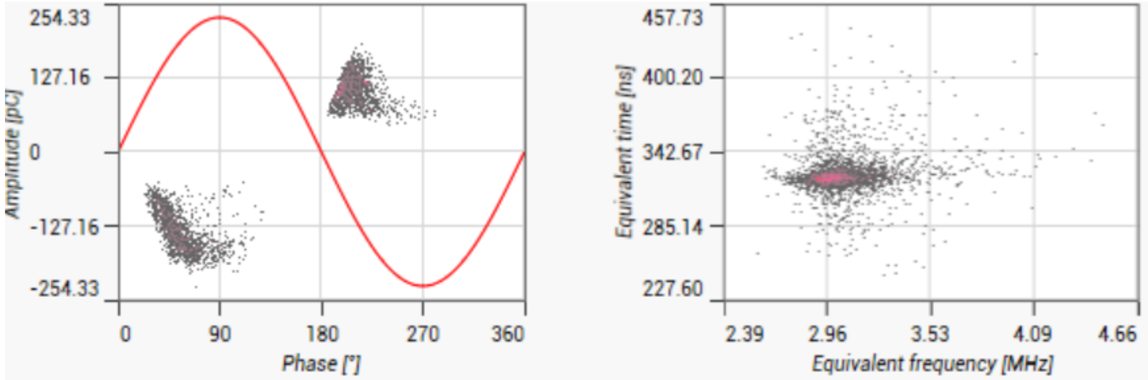




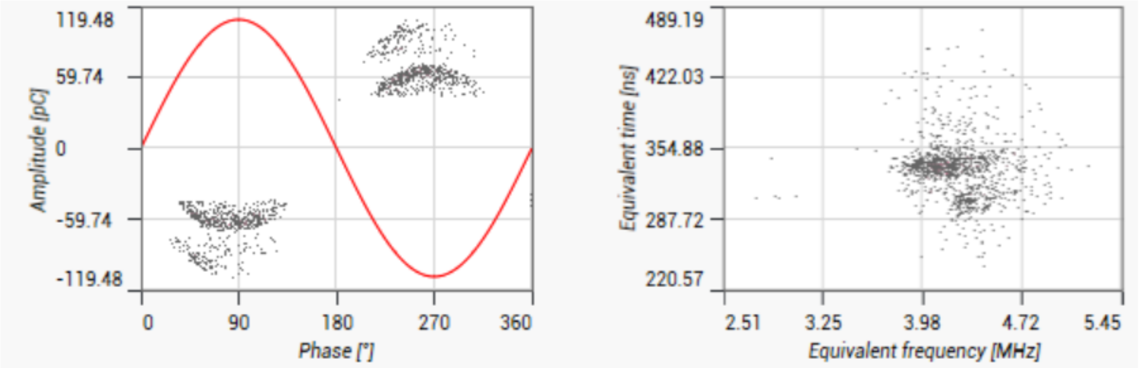
A2, turn 10, 4 kV (Air): **Surface + Internal**



A2, turn 3, 5.8 kV (Oil): **Treeing in Kapton**



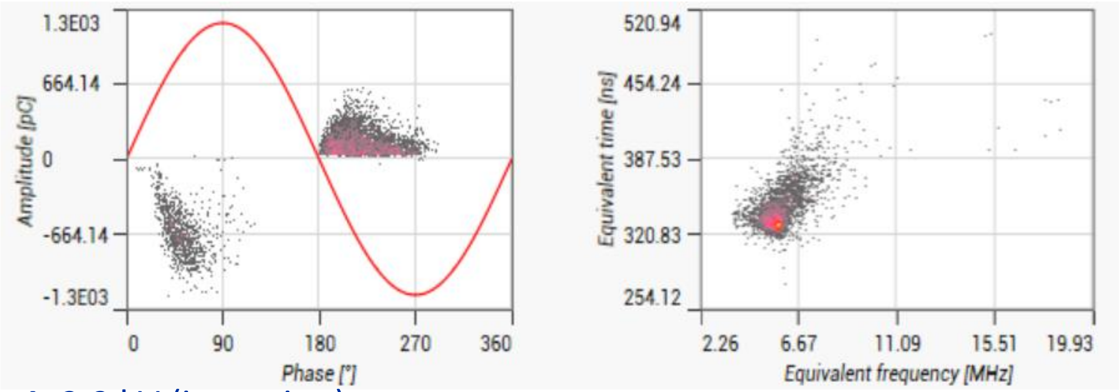
B1, turn 5, 1.8 kV (Oil): **Flat Cavity Discharge (Delamination)**



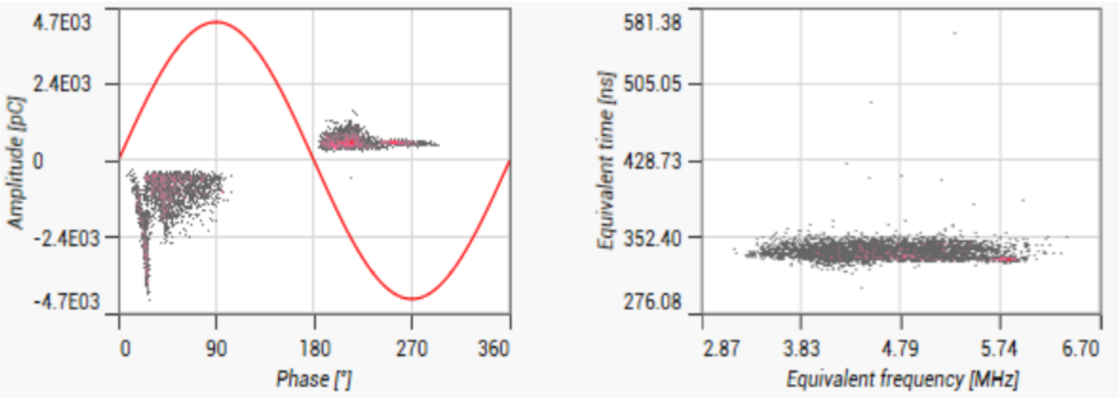
B1, turn 3, 5.5 kV (Oil): **Spherical Cavity Discharge (Micro-Voids in Epoxy)** (<40 um size)

PD: Voltage Amplitude Effects

- A2 tested in oil
- Internal with surface behaviour (along cracks or delaminations)

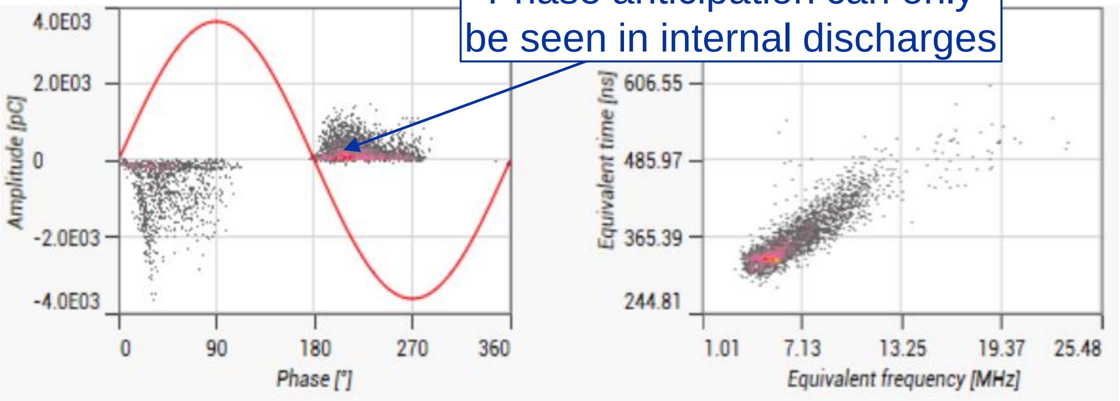


4: 2.9 kV (inception)

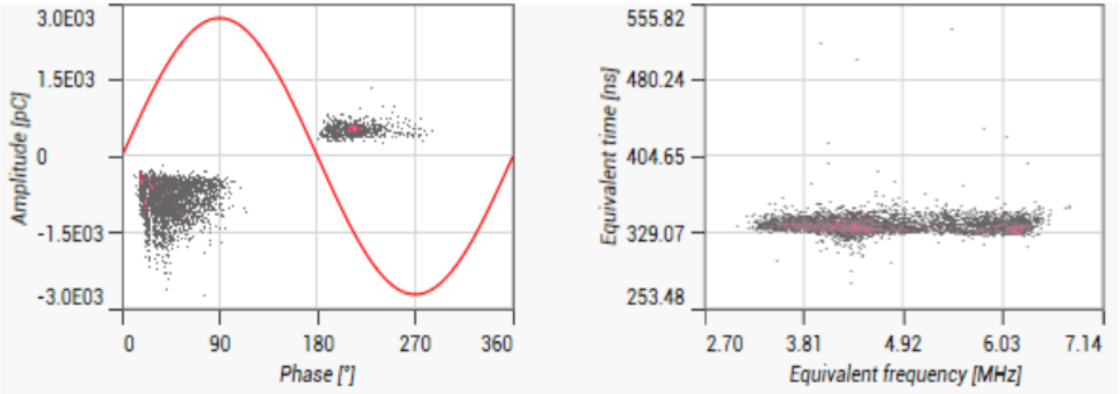


4: 4 kV

Phase anticipation can only be seen in internal discharges



4: 3.5 kV

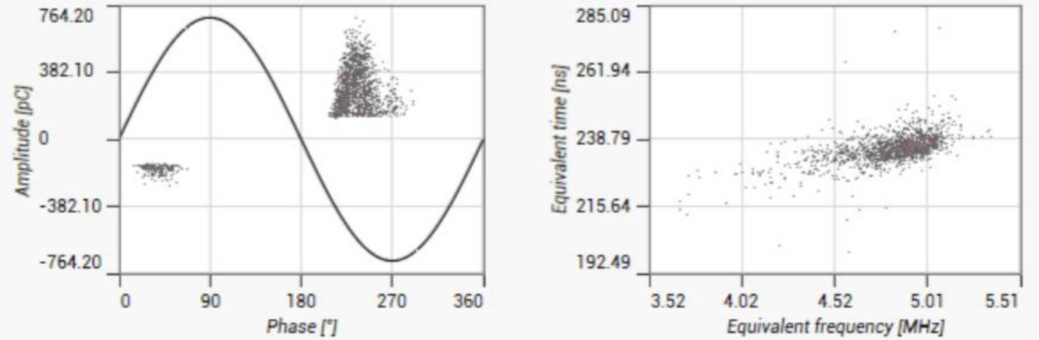


4: 4.5 kV

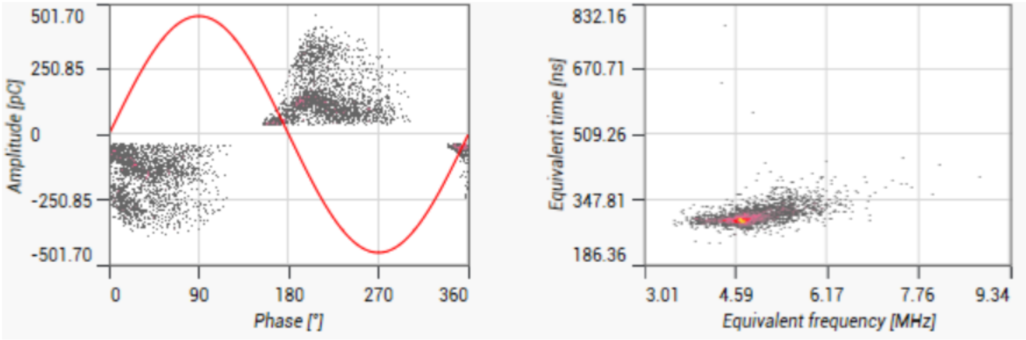
PD Test Results: A2 (oil)

A2: Average inception voltage 4.6 kV

- Notable PD activity shown just in insulation layers between cables 4-5 and between 9-10



5,6: 3 kV, inception 2.9 kV (Oil)

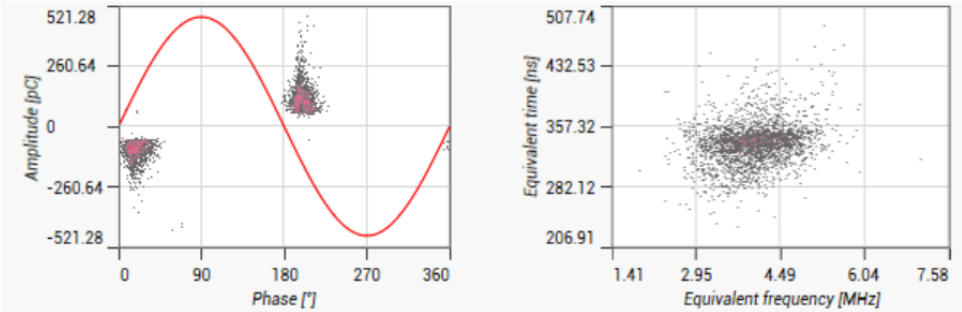


9: 5.8 kV, inception 5 kV (Oil)

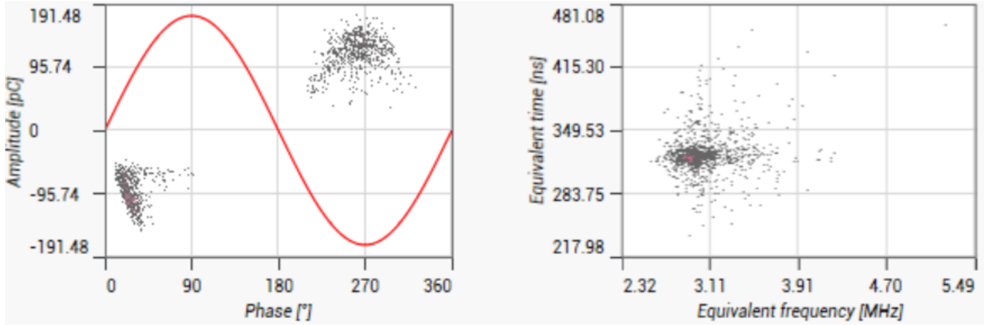
PD Test Results: B1 (oil)

B1: Average inception voltage 3 kV

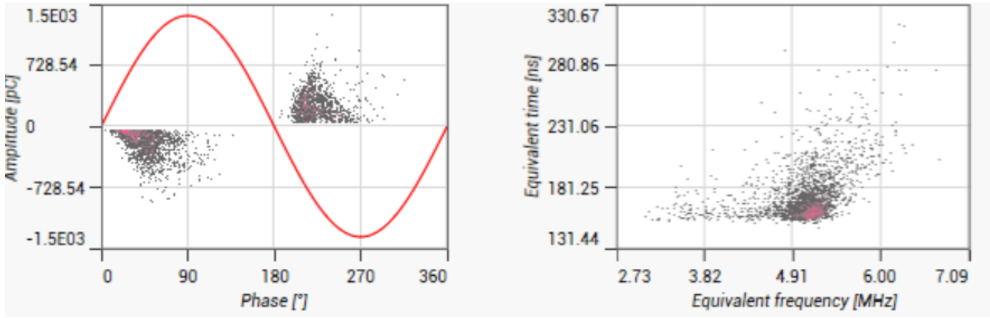
All turns showed defects except for insulation layers between 1-2, 2-3, 3-4.



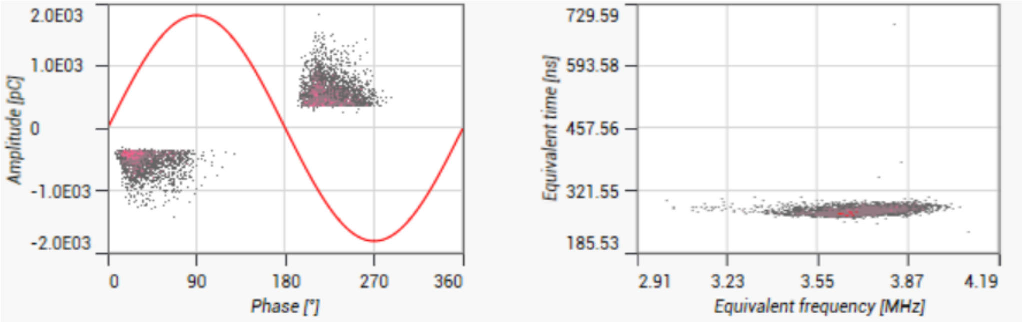
4: 3.5 kV, inception



6: 1.8 kV, inception



7-8: 1.4 kV, inception



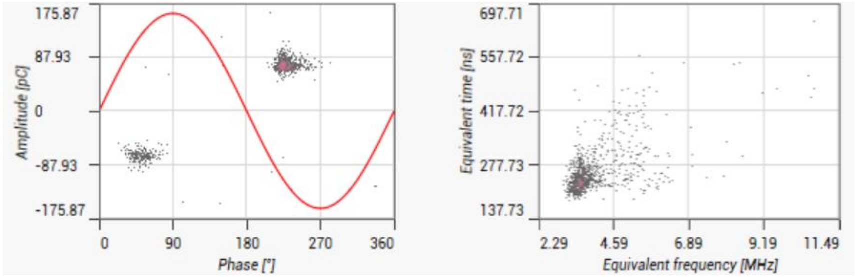
10: 2 kV, inception

PD Test Results: A1 (oil)

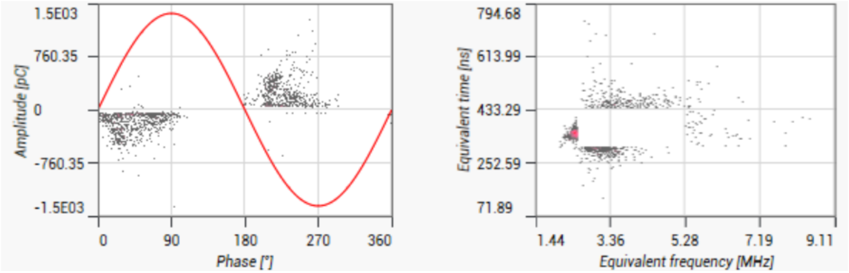
Tested after 5 thermal cycles to LN2: several cracks in connection area (Not reinforced with Nomex)

A1: average inception voltage 2.3 kV

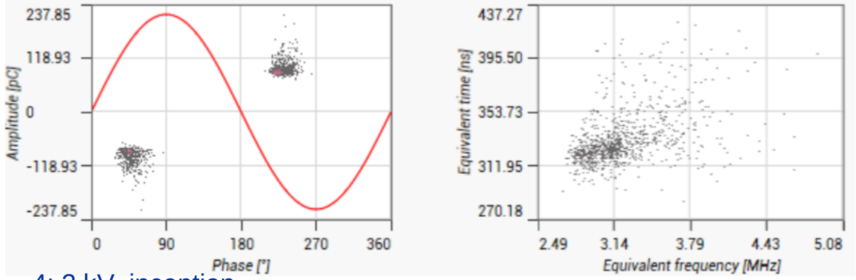
- Low Vi, patterns coherent with discharges along cracks and delaminations



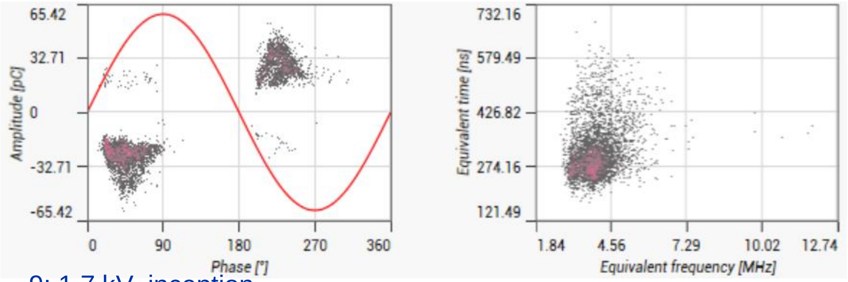
2: 3.5 kV, inception



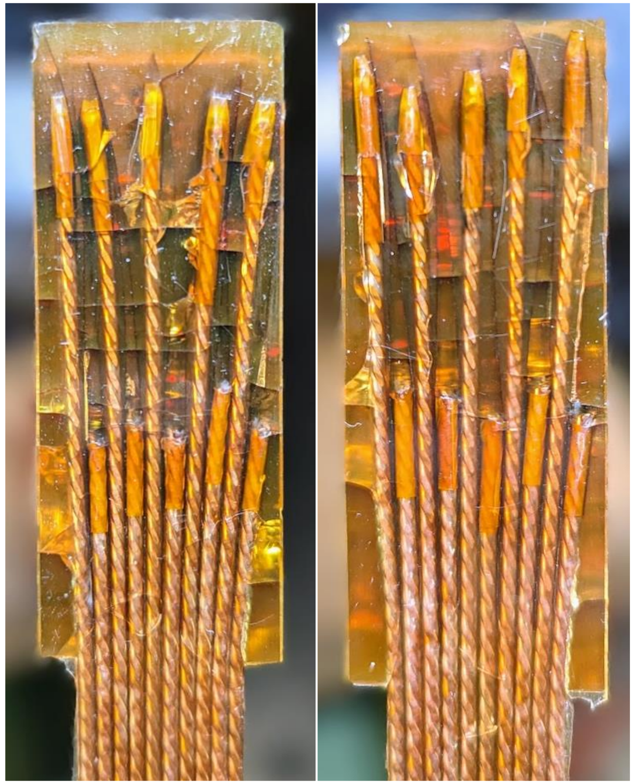
6: 3.7 kV (inception 2.5 kV but stopped after 1000 pulses)



4: 2 kV, inception



9: 1.7 kV, inception



Cracks in the connection area of Stack A1

Discussion

- **A1 (Baseline fiber +CTD101k)**: bad results attributable to cracks in the connection area, not to the insulation itself.
- **B1 (Double layer S2 Glass 11 tex + CTD101k)**: good in some turns, bad in others: problems with the impregnation or with the insulation layout?
- **A2 (Baseline fiber + Polab Mix)**: best results.

- Compared with IR tests, several more information about the condition of the insulation can be obtained.
- Care must be taken in the protection of the connection areas for instance with Nomex fiber.

Conclusion and Future Work

Conclusion

- Interesting results gained regarding dielectric strength and fiber content in the laminates study.
- Insights on the relation between fiber content, carbonized sizing, and low temperatures regarding electrical properties.
- HV 10-Stacks feasible with good reproducibility.
- Collected data regarding turn-to-turn insulation resistance.
- PD analysis of HV 10-Stacks provided deeper insights into insulation conditions compared to traditional IR testing.

Baseline work for future research

Future Work

- More work on desizing to appreciate the advantages of higher fiber content.

- Mechanical tests on plates to assess the effect of fiber content, carbonized sizing, coupling agents.

- Systematic study of PD patterns on HV 10-Stack:
  - At varying voltages
  - After thermal cycles
  - Comparison between measurements in air, oil, vacuum, helium.

- PD in LN2 of reacted HV 10-Stacks

- Turn-to-turn dielectric strength

- Further studies on Volume Fiber Fraction of braided cable insulation

Thanks for everything to all of you

Merci pour tout à tous